Composites 2000

An International Symposium on Composite Materials

October 5–8, 1999
Trabant University Center
University of Delaware

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13. ABSTRACT (Maximum 200 words)

The University of Delaware Center for Composite Materials (UD-CCM) celebrated its 25th anniversary from October 5-8, 1999, with an international symposium, *Composites 2000: An International Symposium on Composite Materials*. The Symposium highlighted advances in composite materials and manufacturing processes by bringing together worldwide leaders in the field of composites to share their extensive knowledge of these topics with representatives of industry, government, and academia. The technical program comprised papers in four theme areas: Materials and Synthesis, Processing Science, Mechanics and Design, and Performance and Durability. Coverage of the current state of the art was complemented by the provision of insight into the future of advanced composites. An abstracts booklet was published, and video of the presentations is available on UD-CCM's Web site at http://www.ccm.udel.edu/mission/comp2000/comp2000agenda.html.

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Foreword

"Composites 2000: An International Symposium on Composite Materials" commemorates the 25th anniversary of the University of Delaware Center for Composite Materials. The objective of the symposium is to highlight advances in composite materials and manufacturing processes by bringing together worldwide leaders in the field of composites to share their extensive knowledge of these topics with representatives of industry, government, and academia.

The technical program comprises papers in four theme areas: Mechanics and Design, Materials and Synthesis, Processing Science, and Performance and Durability. Coverage of the current state of the art is complemented by the provision of insight into the future of advanced composites for the next millennium. These topics were selected based on the philosophy that processing creates microstructure, which determines properties; in turn, properties coupled with environment determine performance, while the objective of design is to predict the effects of all of these interrelated variables. This philosophy has formed the foundation of the Center's research program for much of the past quarter century, and it permeates the technical program of the International Symposium on Composite Materials.

Speakers for Composites 2000 were chosen from an international pool of prominent researchers in composite materials, including past winners of the Medal of Excellence in Composite Materials as well as distinguished alumni of the University of Delaware who now hold respected positions in academia, government, or industry.

This symposium celebrates the Center's 25 years of contributions to the science and technology of composite materials and commemorates its significant role in educating scientists and engineers.

R. L. McCullough

Symposium Chairperson
Prof. Roy L. McCullough

Roy L. McCullough, Professor of Chemical Engineering, was co-principal investigator of the ARO/URI program at UD–CCM, based on his longstanding awareness of DoD needs, his strong background in composites science and technology, his outstanding scholarship, and his industrial/administrative experience. Prior to joining the University of Delaware faculty in 1971, Prof. McCullough worked in the private sector, primarily for the Chemstrand Research Center of the Monsanto Company and for Boeing. He has published widely in the field of polymers and polymer composites and is the author of a book, *Concepts of Fiber-Resin Composites*. Dr. McCullough has served as Associate Director and Director of CCM, and he is currently a member of the Center's Advisory Board. He has contributed to the education of hundreds of students during his career and collaborated with many of the world's leading scientists and engineers in the field of composites.

Micromechanics of Damage in Composite Materials

Zvi Hashin
Faculty of Engineering
Tel Aviv University
Ramat Aviv, Israel, 69978
Voice: (972) 3-640-8522
Fax: (972) 3-640-7617
E-mail: hashin@eng.tau.ac.il

In this talk, the word *damage* implies an accumulation of many defects in the form of microcracks. This is the primary form of damage encountered in composite materials. There are two major goals. The first is to evaluate the degradation of properties such as stiffness end thermal expansion coefficients (TEC) due to such damage. The second is to actually predict the accumulation of damage. The expression *micromechanics* implies analytical methods which recognize explicitly the nature of the defects (cracks) but not necessarily their precise locations. This in contrast to continuum damage mechanics, where damage is described implicitly in terms of abstract entities.

Evaluation of degradation of properties is of necessity based on approximate analysis. The simplistic well-known shear-lag method has been outmoded by more sophisticated and more accurate methods. Here the variational method is emphasized, its advantage being that it is concerned not with just one approximation, hopefully well chosen, but with a whole family of approximations optimized to choose the best one. Stiffness and TEC degradation of cracked laminates are discussed on this basis.

Prediction of damage accumulation implies here prediction of crack densities and perhaps other related statistical quantities of crack distribution produced by given load/temperature input. This is a fracture mechanics–related problem, but it cannot be approached by classical methods, since it involves many interacting cracks which appear spontaneously. The problem is here considered in terms of a novel criterion for spontaneous crack formation in a brittle elastic body in the presence of thermal residual stress. This criterion is applied to prediction of crack density in a laminate subject to tensile load and/or temperature change.

Imperfection is a deviation from an ideal situation which may be called perfect. The present discussion of imperfection is confined to composite interfaces. At a classical perfect interface, the displacement and stress vectors are continuous. At an imperfect interface, each or both may be discontinuous. Such an imperfect interface is in actuality a simplified model for a thin interphase—for example, between fibers and matrix—which is formed due to chemical action or degradation of bonding. The possible implications of an imperfect interface are discussed here on the basis of analysis of unidirectional fiber composites with an imperfect interface.

Composite Materials and Structures Technologies at NASA Langley Research Center

Mark J. Shuart
NASA Langley Research Center
Structural Mechanics Division
Mail Stop 242
Hampton, VA 23681-0001
Voice: (757) 864-3492
Fax: (757) 864-7792
E-mail: m.j.shuart@larc.nasa.gov

Composite materials and structures technology has made a significant impact on a wide variety of aerospace systems. This technology is being used for primary structures of a subsonic commercial transport aircraft (empennage structure for the B-777), an experimental reusable launch vehicle (hydrogen tanks for the X-33), and a high-performance military aircraft (Lockheed-Martin F-22). The technology has also been baselined for future high-speed civil transport and many spacecraft structures. As part of the technology development, many lessons have been learned along the way. These lessons will be the foundation for future applications of composite materials and structures.

This paper will describe lessons learned for composite materials and structures technology, recent developments for this technology at the NASA Langley Research Center, and future technology applications. Lessons learned will be presented by discipline areas: materials, processes, and manufacturing; structural design, analysis, and testing; and quality control, nondestructive evaluation/inspection, and supportability. Recent accomplishments for new materials, improved processing, revolutionary structural concepts, advanced analytical methods, and quantitative nondestructive evaluation techniques will be described. The application of composite materials and structures technology to reusable launch vehicles and to spacecraft will be discussed. These applications will build on the lessons-learned foundation and apply technologies described by the recent accomplishments. New technologies for materials, processing, structural concepts, and sensors will enable dramatically improved future applications.

Mechanics of Composites As Related to Design Issues

James M. Whitney
Department of Civil and Environmental Engineering and Engineering Mechanics
University of Dayton
300 College Park
Dayton, OH 45469-0243
Voice: (937) 229-2979
Fax: (937) 229-3491
E-mail: jwhitney@engr.udayton.edu

As we look through the development of mechanics of composite materials, certain accomplishments that have had a clear impact on design can be readily identified. For example, classical laminated plate theory has become a standard tool for the designer. Within the framework of classical laminated plate theory, one can accurately calculate effective elastic constants for symmetric laminates in terms of in-plane and bending loads. In-plane ply stresses under in-plane and bending loads can also be readily calculated. For thin laminates, interlaminar stresses, away from free edges, can be determined by integrating the equilibrium equations of classical theory of elasticity in conjunction with the in-plane loads. Thus, classical laminated plate theory has become a powerful tool for stress analysis in preliminary design. Various versions of classical laminated plate theory have also been incorporated into finite element codes for stress analysis of complex structures. Issues such as free vibration frequencies and critical buckling loads can be handled for thin plates within the framework of classical laminated plate theory. For thicker plates, various extensions of classical laminated plate theory to shear deformation theories have been attained to handle bending loads, free vibration frequencies, and critical buckling loads. Over the past decade, models developed within the framework of laminated plate theory have also emerged in conjunction with preforms other than unidirectional prepreg tape. For example, models which deal with fabric and braided structure, as well as models for sandwich type structures, are readily available.

Concerns over free-edge stresses and their impact on design have emerged over the past two decades. Various models, including finite element, can be found in the literature. Unlike issues addressed by classical laminated plate theory, a clear consensus on a single approach to free-edge stress analysis does not exist. Some excellent approaches exist for free-edge stress analysis along straight edges. The problem becomes much more complex, however, when addressing curved boundaries, such as open holes. The need to perform free-edge stress analysis, especially in such complex cases as open holes, in conjunction with actual design situations is not completely clear at this point in time.

Thus, we may conclude that considerable progress has been made in the area of stiffness analysis and stress analysis to support structural designs incorporating composite materials. Although problems associated with strength prediction have been with us since the onset of advanced composite materials in the late 60s and early 70s, failure criteria (especially for in-plane loading) is still a controversial area. In fact, many workers fail to separate stress analysis from failure criteria. For example, when failure predictions do not match experimental data, we often hear that "lamination theory doesn't work." Such statements fail to recognize that strength analysis comprises two key components, a stress analysis and a failure criterion. Lamination theory may well produce accurate stress predictions, but if the failure criterion is lacking, the resulting predictions will not be acceptable. In the area of out-of-plane failure such as delamination, fracture mechanics has found a niche. Onset of delamination predictions is more complex because of the lack of a clear stress analysis tool in addition to the usual difficulties associated with failure criteria.

Progressive damage—that is, failure beyond what is considered first-ply failure—is not clear cut, although more light has been shed on this issue in recent years with the emergence of ply cracking and delamination models.

This presentation will focus on issues surrounding failure criteria and the need to identify failure modes in the selection of an appropriate failure criterion. In addition, the interaction between initial ply failure and progressive damage will be explored. Ramifications of these issues relative to materials characterization will also be discussed.

Mechanics of Corrugated-Core Sandwich

Leif A. Carlsson
Department of Mechanical Engineering
Florida Atlantic University
500 Northwest 20th Street
Boca Raton, FL 33431–0991
Voice: (561) 297-3420
Fax: (561) 297-2825
E-mail: carlsson@fau.edu

To develop improved structural design of corrugated board packages, a research project was initiated at SCA Research in Sweden. Initial efforts were directed at predicting the various in-plane and out-of-plane structural stiffnesses of corrugated core sandwich panels (Figure 1), defined in the equations below:

$$\begin{bmatrix} N_x \\ N_y \\ N_{yz} \\ N_{xz} \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & 0 & 0 \\ A_{12} & A_{22} & 0 & 0 & 0 \\ 0 & 0 & A_{44} & 0 & 0 \\ 0 & 0 & 0 & A_{55} & 0 \\ 0 & 0 & 0 & 0 & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} \begin{bmatrix} D_{11} & D_{12} & 0 \\ D_{12} & D_{22} & 0 \\ 0 & 0 & D_{66} \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

where A_{ij} denote "extensional" stiffnesses and D_{ij} "bending" stiffnesses. The accuracy of the analytical predictions was examined in a parallel effort where test methods and data reduction methodologies were developed.

For modeling the mechanical response of relatively large panels, it is not practical to consider the geometrical details of the corrugated core. For this purpose, analysis methods were developed to contain the effective properties of the corrugated layer.

In this presentation, we will review the analysis methods for obtaining the stiffness and effective core mechanical properties and compare predictions to experimental results and numerical (finite element) calculations.

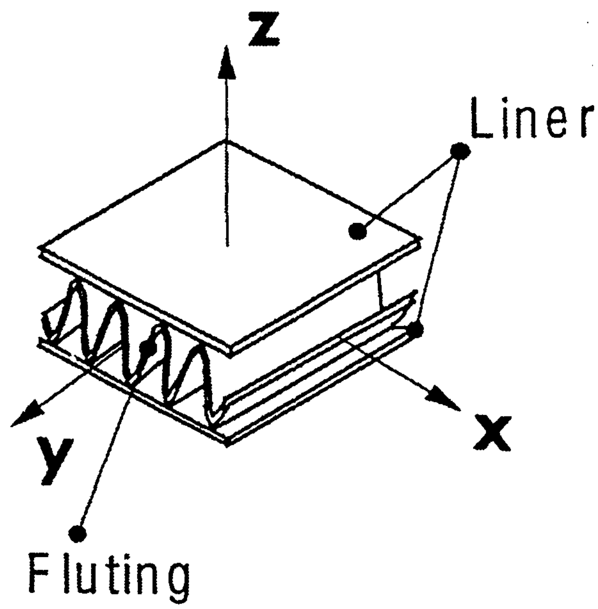


Figure 1: Corrugated core sandwich panel.

Composites in the Context of 21st Century Materials Science and Engineering

Anthony Kelly
Churchill College Cambridge CB3 ODS, UK
Department of Materials Science and Engineering
University of Cambridge
Pembroke Street
Cambridge CB2 3QZ, UK
Voice: (44) 1223-334-329
Fax: (44) 1223-334-567
E-mail: ak209@cam.ac.uk

The reasons for the increased interest in the properties and production of "natural fibers," or those that can be grown and harvested in quantity, will be reviewed. The interest stems mainly from environmental concerns and the need to dispose of structures at the end of their lives.

Consideration of natural fibers leads to consideration of "natural structures" containing fibers. In these, it is claimed that fibers are grown by nature in directions tuned to match a dynamic stress field. The fibers are put in place and the matrix assembled afterwards. This notion runs counter to the idea that the properties of a fibrous composite should be stated in terms of the well-known "bulk" properties of materials. And again it is claimed, rightly, that civil engineers design reinforced structures by considering first the overall shape in, say, concrete and then distributing bars in an appropriate way to carry the tensile stress field. A fusion of these ideas involves the notion of a defining size either of a piece or of a structure.

An attempt to design an arrangement of fibers which would be elastically isotropic leads to a somewhat similar conclusion—namely, that equiaxed particles at similar volume fractions to the fibers are more efficient. How far particles and fibers can be mixed is becoming a very important problem for composite material development.

Once the question of the internal geometry is raised, equal attention must be given to the planar layered composite and the fibrous composite. Some recent experiments on the fracture toughness of laminates and on the strength of laminates will be described. This will be coupled with remarks on the present state of development of metal-matrix composites and the use of composite materials for thermal management problems.

Finally, the rise of the importance of modeling by computer simulation in materials science and engineering will be emphasized and the importance of this for composite material development accentuated.

Trends of Polymeric Composites Applications

I. Crivelli Visconti
University di napoli Federico II
DIMP
Piazzale V. Tecchio 80125 Italy
Voice: (39) 081-768-2366
Fax: (39) 081-672-7826
E-mail: crivisco@unina.it

After about a decade of crisis in applications of composite materials in all industrial sectors from aeronautical to sporting goods due to the economic recession, recent years have witnessed a new upswing and a continuous growth in composites research and applications.

On this note, a perspective on recent innovative applications of composites and on future further uses, as pointed out by outcomes of recent studies, is presented.

Attention has been principally focused on engineering sectors in which composites are finding new applications (civil, biomedical, sporting goods), but without ignoring sectors in which the use of composites is already widespread but continuously growing with the development of computer-aided design techniques and of composite materials resistant to severe environmental conditions (aerospace and transport sectors).

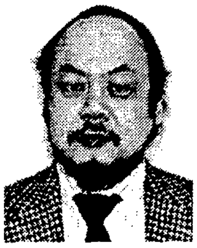
Automated placement with in-situ e-beam cure will require a faster cure mechanism than is now available.

Low-temperature thermal, microwave, or induction curing may be done if the right epoxy can be developed. The idea is to cure to a green stage at temperatures around 150°–175°F, preferably ply-by-ply, and postcure in an oven. Low-cost tooling might be applicable both with these and the e-beam method, depending on the ultimate cure temperature.

RTM, VARTM, and RI processes can be employed with just a thermal cure and are the ones most likely to see application first, since they require the least development. Interestingly, these techniques have been expanded into the high-temperature range with the development of polyimides that have very low viscosities at reasonable temperatures. Their application to future space vehicles possessing hot structure is very enticing since, if the skins are allowed to get hotter, the thermal protection system can be cut back, thereby saving weight.

Heated head automated placement of thermoplastic ribbon and tape is another nonautoclave technique worthy of consideration. The government-sponsored RAPTECH and HSR Programs have matured this technology to the point where near-autoclave properties can be obtained with materials such as PEEK and PIXA-M. A sound database needs to be established, and further refinements to the technique are required to build complex structure.

Overview of Japan's CMC Research Activities Supported by Textile Technologies



Takashi Ishikawa
National Aerospace Laboratory
Airframe Division
6-13-1 Ohsawa, Mitaka,
Tokyo 181-0015, Japan
Voice: (81) 422-31-1186
Fax: (81) 422-31-6198
E-mail: isikawa@nal.go.jp

Introduction

Ceramic-matrix composites (CMCs) are among the most promising candidate materials for high-temperature components in some aerospace applications. In Japan, R&D programs for realizing such material systems and applying them to vehicle components are being actively pursued. Textile products such as 3-D fabrics and stitched or braided tubes made of ceramic fibers are frequently employed as CMC reinforcements. This presentation (1) re-examines the technical basis for the use of textiles as reinforcement, (2) surveys key techniques other than textiles for stronger and more environmentally resistant CMCs, and (3) introduces examples of CMC aerospace vehicle components for future applications.

Reasons for Textile Reinforcements

There should be clear engineering reasons for why textile products are suitable for CMC reinforcements. A perspective is given here based on the author's long-time experience. Note that the polymer impregnation and pyrolysis (PIP) technique is mainly utilized in Japan for matrix consolidation.

1. **Shape Stability During Material Fabrication**—When the author's group (NAL, Ube Industries LTD, and Shikibo LTD—and lately Kawasaki Heavy Industries LTD, or KHI) started CMC research work in Japan, 3-D fabrics were employed and have been utilized throughout the programs [1]. Their initial idea was to maintain a minimal level of translaminar strength. However, among the lessons learned during development, the most important is that the sturdiness of 3-D fabric contributes to maintenance of the initial shape of the reinforcement during PIP processing. Trial usage of 2-D fabrics led to serious fiber crimp and caused voids and low strength. In general, molds for PIP are simple, but in the case of complex shapes, particularly if the types of 3-D fabric are limited, a compensating technique is stitching, or Z-plus (Shikibo), which is a stitched-like product suitable for complicated components. By such techniques, CMC quality via PIP can be maintained.

2. **Straightness in In-Plane Tows**—This advantage is related to the previous point. Although 3-D fabrics suffer a slight sacrifice in fiber volume fraction, load-carrying in in-plane tows is generally excellent. Figure 1 shows one example of SCL type 3-D fabric. In CMCs, strength reduction by fiber crimp is generally serious compares with polymer composites.

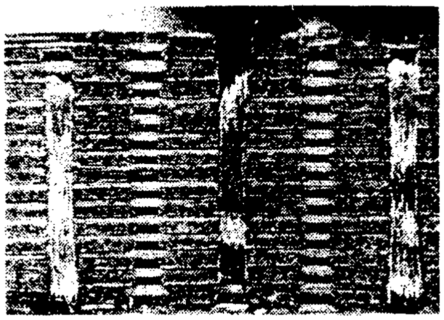


Figure 1: Section of SCL 3D fabric.

3. Translaminar and Interlaminar Strengths—As stated earlier, this substantial merit of 3-D is not of priority importance at the present design level of CMCs. In the future, strength characteristics other than in-plane will be reflected to design of CMC components.

Keys for Stronger and More Endurable CMC

Several important technologies for better CMCs developed in Japan are briefly introduced. Although BN coating is a typical interface of fibers for stronger CMCs, Ube Industries Co. developed a new interface modification technique based on chemical-physical treatment for their Si-Ti-C-O fibers, Tyranno®. Among several types, TM-S6 treatment provides the best composite tensile strength, and its Auger analysis is comparatively shown in Figure 2. A subtle change in the fiber surface brings optimal fiber-matrix sliding shear stress and results in the best strength.

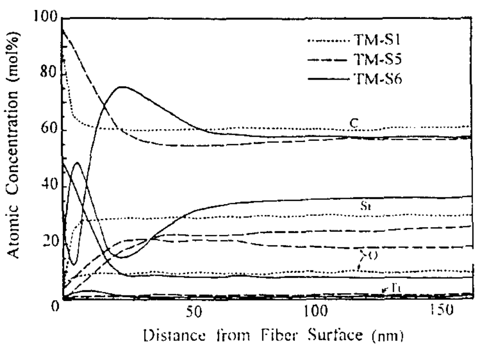


Figure 2: Results of fiber surface treatment.

The next technique is a glassy sealant for oxidation resistance at high temperature developed by KHI. The sealant consists of a family of Na_2O-SiO_2 water glass, which is impregnated by vacuum technique and treated by heat into a sort of glass. Multiple repetitions of the sealing process are effective in increasing glass content and therefore oxidation resistance. However, this process will charge a penalty of 10% weight increase. Creep rupture strengths at elevated temperatures are shown in Figure 3. If no sealant is used, static strengths at these temperatures are reduced to one third, and creep strengths are reduced to almost nothing. Thus, this surface is crucial for good oxidation resistance of the present CMCs.

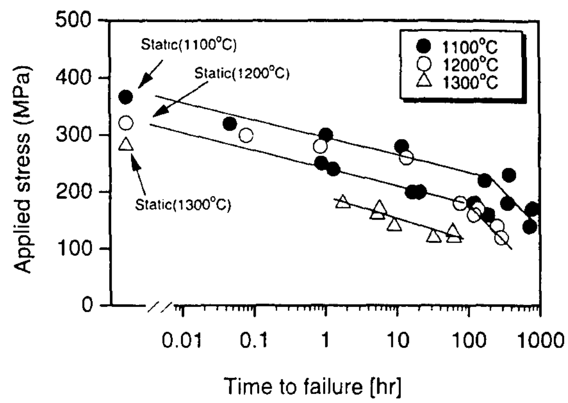


Figure 3: Creep rupture strengths of glass sealed CMC at elevated temperature.

Examples of CMC Components under R & D

Based on the above-mentioned achievements, several development activities are ongoing in Japan. For space transportation systems, research is quite active considering requirements for reusability. A demonstration-level model for a CMC leading edge was fabricated through the NAL-Ube-Shikibo team. Z-plus® (like stitching) is used as reinforcement in this model. In Japan's space-shuttle-like vehicle, CMCs may be actually used in control surface, or TPS.

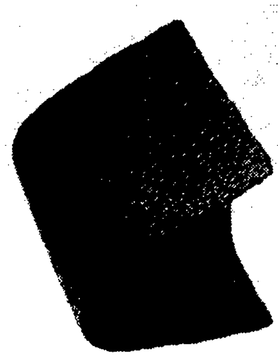


Figure 4: Model for leading edge of re-usable launch vehicle.

As the other example, a combined unit of turbine disk and blades (bl-isk) based on 3-D fabrics containing radial and axial fibers is shown in Figure 5 [2]. Although these kinds of activities are still in the demonstration phase, some will be applied in the next decade.

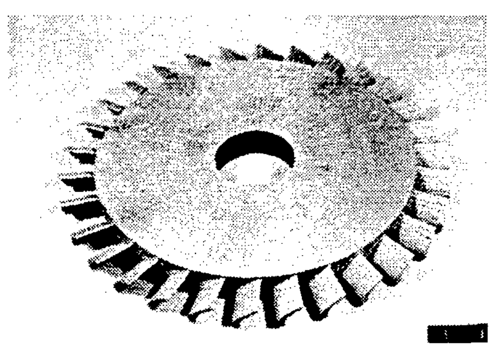


Figure 5: Model turbine disk with blades.

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Going from Polymers to Ceramics in Composites Manufacturing

Selçük I. Guçeri, Professor and Head
Department of Mechanical Engineering
University of Illinois–Chicago
2037 Engineering Research Facility
842 W. Taylor Street
Chicago, IL 60607
Voice: (312) 996-5096
Fax: (312) 413-0447
E-Mail: Guceri@uic.edu

Abstract not available.

Directional Solidified Intermetallic and Ceramic Eutectic Composites for High-Temperature Applications

Jenn-Ming Yang
Department of Materials Science and Engineering
University of California
405 Hilgard Avenue
Los Angeles, CA 90095-1595
Voice: (310) 825-5534
E-mail: jyang@seas.ucla.edu

Intermetallics and ceramics are potential materials for a variety of high-temperature structural applications in oxidizing environments. However, to make them a viable structural material, it is necessary to overcome some of their inherent problems. These include low ductility and fracture toughness at ambient temperatures and inadequate strength and creep resistance at elevated temperatures. Recent studies have indicated that the composite approach is a promising way to overcome many of these inherent deficiencies. The composite may be produced in-situ or artificially by juxtaposing individually identifiable matrix and reinforcement materials. While the approach appears simple and promising in principle, it is limited in practice by the availability of compatible fibers, controlled processing, and microstructural homogeneity and reproducibility.

Alternatively, the composite microstructure may be created in-situ either synthetically or naturally. The in-situ composite approach seeks to produce a two- or multi-phase composite microstructure in a controlled, non-mechanical fashion. The ideas of reinforcing intermetallics and ceramics in-situ by directional solidification technique were actively pursued in the early 1970s. Recently, however, there has been renewed interest in developing intermetallic- and ceramic-based eutectic composites for high-temperature structural applications. This is primarily motivated by the advancement of processing technology, which has led to better control of processing parameters and high processing rates. For example, ceramic eutectics with aligned structures have several intrinsic characteristics: excellent oxidation resistance, microstructural stability up to temperatures approaching the eutectic temperature, and good compatibility and bonding between phases. The phases are uniformly distributed, and their spacing, which can be controlled if small, may limit the size of microcracks. Many intermetallic/refractory metal and oxide/oxide eutectic composites with fibrous or lamellar microstructure have been successfully fabricated by directional solidification techniques such as Laser-Heated Floating Zone (LHFZ) and Edge-defined Film-fed growth (EFG).

The processing, microstructure, and properties of several intermetallic/refractory metal (NiAl/Cr(Mo), Cr_2Nb/Nb) and oxide/oxide (YAG/Al_2O_3, Al_2O_3/ZrO_2 (Y_2O_3)) eutectic composites will be presented. The prospects of achieving a strong and tough in-situ intermetallic and ceramic composite through controlled solidification will also be discussed.

Durability of Bonded and Bolted Joints of Composite Laminates

Stephen W. Tsai
Stanford University
Department of Aeronautics and Astronautics
Durand Building, Room 381
Stanford, CA 94305-4035
Voice: (650) 725-3305
Fax: (650) 725-337
E-mail: stsai@structure.stanford.edu

Bonded and bolted joints in composite structures may drive many design considerations. Without a consistent and rational basis, joints can be either unsafe or costly.

Our approach to the durability issue during the recent past has been based on the time-temperature superposition hypothesis. A database of static, creep, and fatigue strengths as functions of strain rates, temperature, and loading conditions have been obtained. With the aid of an automated shifting program, called Auto-Shift, master curves of these strengths can be generated and validated by experimental data.

It is feasible to predict the life of a composite laminate as a function of loading conditions that include frequencies, stress ratios, and temperatures of the applied tensile or compressive load. A number of design variables such as the adhesive thickness and ductile versus brittle adhesives have also been included in the study.

For bolted joints, the effects of bolt tension, washer geometry, and fabrics versus laminates have been included.

With master curves based on a linear cumulative damage law, life prediction and test acceleration can be readily carried out.

Study of the mechanisms of failures has to be verified as required by the superposition hypothesis.

This approach provides a basis for design allowables which can now be rationally selected and generated with easy-to-determine accelerated testing.

Durability of Composites for Rotorcraft Applications

T. Kevin O'Brien
U. S. Army Research Laboratory
Vehicle Technology Directorate
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23681
Voice: (757) 864-3465
Fax: (757) 864-8911
E-mail: t.k.obrien@larc.nasa.gov

Laminated composites are being used in the design of helicopter rotor hubs that are both hingeless and bearingless, thereby reducing weight, drag, and the number of parts in the hub. During flight, the hub is subjected to constant tension loading from the centrifugal forces, as well as bending loads in the flapping-flexure region. The thickness of the laminated flexbeam is reduced along the length by dropping, or terminating, internal plies. Delaminations occur near these ply-drop locations. In a recent study [1], one-inch wide coupon specimens were cut from a full-size flexbeam of S2/E7T1 glass/epoxy and tested under combined tension-bending loading in a servo-hydraulic load frame which was designed and built to produce the desired combined tension-bending loading. A transverse displacement was chosen that would produce the same maximum surface strains experienced by the full-scale flexbeam. Cyclic transverse displacement was applied under displacement control, using a frequency of 3 Hz and fully reversed loading. Under the combined loading, delamination cracks typically started in the areas around the ply-drop locations. As the loading continued, delaminations grew in both directions away from the ply drops. Loading continued until the specimens delaminated completely along one or both edges. A geometric nonlinear finite element model of the tapered laminate was developed and analyzed to determine the stresses and strains in the flexbeam specimens. The analysis was able to replicate the global response of the test specimens under load, in terms of tip-displacement, flapping angle, and surface strains. Strain energy release rates associated with delamination growth were calculated using the Virtual Crack Closure Technique (VCCT). This information was used, along with material characterization data, to predict delamination in the flexbeam specimens under fatigue loading.

Bonding or co-curing of stringers to skins is attractive because of the reduced manufacturing cost compared to mechanically fastened structures. However, out-of-plane loading, such as internal pressure in a fuselage or post-buckling of a skin panel, may cause debonding. The damage mechanisms in composite bonded skin/stringer constructions under combined tension and bending loads were documented using specimens consisting of a tapered flange, representing the stringer, bonded onto a skin laminate [2]. Both the skin and stringer laminates were made of IM6/3501-6 graphite/epoxy prepreg. Tests were performed in tension, 3-point bending, and combined tension/bending. For the biaxial testing, a unique servohydraulic load frame was used that was capable of applying both loads simultaneously. Microscopic investigations of the specimen edges were used to document the damage and to identify typical damage patterns. The observations showed that, for all three load cases, matrix cracks initiated in the off-axis flange plies near the flange tip, causing the flange to almost fully debond from the skin. A two-dimensional, plain strain, finite element model was developed that closely approximates the specimen geometry, the boundary conditions, and the three loading conditions applied during the tests. All three load cases were analyzed using the geometrically nonlinear solution option of the ABAQUS finite element code. For all three load cases, matrix crack formation occurred when the principal tension stress in the 2–3 plane of the off-axis flange plies reached the transverse tensile strength of the material. A fracture mechanics approach was used to determine the potential for delamination growth from the initial transverse crack. Mode I and Mode II strain energy release rate contributions were calculated for all load cases using the virtual crack closure technique. Computed total strain energy release rates were compared to critical values obtained from an existing mixed-mode failure criterion. In addition, a simple technique was developed to generate G components as a function of delamination length using only a single non-linear analysis and simulating delamination growth in smaller linear models with unit load conditions [3]. This technique may then be used for parametric design studies in such a way that only a few finite element computations will be necessary for a study of many load combinations.

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Designing for Durability in PMC Structures

Keith T. Kedward
University of California at Santa Barbara
Department of Mechanical & Environmental Engineering
Engineering II Building
Santa Barbara, CA 93106-5070
Voice: (805) 893-3381
Fax: (805) 893-8671
E-mail: kedward@engineering.ucsb.edu

Summary

The design of composite structures that are to be exposed to high cyclic loads and frequent environmental hazards represents a continuing challenge for the developer and producer of durability-driven products. Despite the extensive resources in the form of fatigue databases and available publications, the large majority of these resources tend to be limited to laminate level and/or coupon level phenomena. This situation is understandably due, at least in part, to one or both of the following:

(1) Generic applicability of coupons comprising essentially 2-D architectures such as laminates or "near laminates" with minimal through-thickness fiber reinforcement.

(2) Economic pressures associated with committing hardware resources and the long-term nature of durability experiments.

In the present paper, the desirable features of fatigue-tolerant laminates and lightly-stitched or interlocked reinforcement architectures are examined and concisely summarized. Both the durability and damage tolerance enhancement introduced by toughened matrices, toughened interlayers, through-thickness reinforcements and sandwich and buffer-strip concepts are systematically evaluated. It is explained that the extent of the enhancements are not necessarily of equal benefit to durability and damage tolerance.

More complex aspects associated with assembled structures that may be comprised of both composite and metallic components connected by bonded and/or bolted connections are included in the presentation of design approaches for specific applications.

Technical Content:

I. Fatigue of Composite Laminates and "Near Laminates"

The design of composite laminates that provide durable as well as damage-tolerant characteristics (in some cases) can be strongly influenced by fiber architecture and the specific application requirements. For the category of two-dimensional, uni-tape or fabric laminates, it is generally recognized that the $[0^\circ_1, +45^\circ_m, 90^\circ_n]$ family represents a relatively durable, damage tolerant configuration when the loading is predominantly 'membrane' in nature. However, the differences between tension and compression-dominated loadings and the characteristics of preexisting defects or damage must also be carefully considered. As an example, it has previously been shown [1] that delaminations produced by damage introduced during fabrication or in-service use, are the major life-limiting mechanism in the presence of membrane compression loading vis-a-vis membrane tension loading.

Specific examples of design approaches that have been adopted in an attempt to enhance either or both the durability and the damage tolerance of composite laminates are summarized in Table 1. The views regarding the relative benefits of the various approaches will be discussed concentrating on those where durability enhancements await more convincing evaluation. In general, the approaches that yield enhanced damage tolerance are more clearly apparent with extensive supporting experimental data. For example, stitched composite architectures have certainly demonstrated improved compression-after-impact strength [2], albeit with measurable deterioration in undamaged strength, whereas durability evaluations are still being researched and will be addressed in this paper.

Table 1. Potential and Proven Design Approaches Used for Durability and/or Damage Tolerance Enhancement

	Potential/Proven Enhancement of	
Design Approach	Damage Tolerance	Durability
Toughened matrix	x	?
Tough interlayers	x	?
Stitching or interlock architectures	x	?
Buffer-strip concepts	x	x
Sandwich skin-core configuration	x	x

II. Fatigue/Durability of Composite Assemblies Involving Joining Concepts

Changes of thickness or direction—i.e., curvature—and structural connections are some of the common sources of out-of-plane loading that result in interlaminar shear and tension stresses. Definition of several of these sources of delamination initiation and propagation was presented previously [3], but in this work the focus will be placed on bonded and/or bolted connections.

First, the primary mechanisms for delamination development arise due to primarily induced peel stress in the case of bonded joints typically at the regions of termination of bondlines. In the case of bolted joints, one of the major concerns is associated with bearing-induced damage that usually results in permanent hole elongation and consequent load redistribution.

One approach to averting these strength and life-limiting damage sources is the "hybrid" joint (bonded and bolted), but such concepts fall into two general categories:

1. Peel fasteners or "chicken rivets" that are used only to suppress the development of peel stresses in the adhesive or mating laminates but do not contribute to the shear load transmitted through the joint.

2. Bonded/bolted joints wherein the bolts contribute a significant, 20% or greater, proportion of the load transmitted.

For category 2, the challenge is to reduce the load contribution of the adhesive by using a more flexible, thicker bondline, for example. The paper will include specific aspects of the design for category 2 hybrid joints that are required to sustain structural loads over long periods of usage.

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The State of the Art of Fine Ceramic Fibers For High-Temperature Reinforcement

Anthony R. Bunsell
Ecole des Mines de Paris-Centre des Matériaux
B. P. 87, 91003 Evry Cedex, France
Voice: (33) 1-607-630-15
Fax: (33) 1-607-631-50
E-mail: anthony.bunsell@mat.ensmp

Small-diameter ceramic fibers, which now are generally based on SiC or alumina, have been proposed for use as reinforcement at high temperatures since the late 1970s. Although alumina fibers were the first to be produced and used to reinforce light alloys, it was the production of the first SiC-based fibers that allowed the possibility of producing structural ceramic-matrix composites that could be used to higher temperatures than the best metal alloys envisaged. Such composites have been limited by the performance of the reinforcements at high temperature, but as the processes limiting their use are better understood, improved fibers are appearing that approach the physical limits of such materials.

Silicon-Carbide-Based Fibers

Fine SiC fibers are prepared by melt spinning, crosslinking, and pyrolyzing an organosilicon polymer. They consist primarily of nanometric SiC grains, although other phases, which are free C, and, in the earlier fibers, a poorly organized metastable intergranular phase of Si-C-O which allows the fiber to creep above 1000°C. The Young's moduli of these fibers are around 200GPa. Since the first Nicalon fibers, produced in 1982 by Nippon Carbon, which uses polycarbosilane (PCS) as a precursor, improvements of the fabrication route and/or modifications of the precursor polymer have permitted the development of other SiC-based fibers by Nippon Carbon, Ube Industries, and Dow Corning. The latter two producers use polytitanocarbosilane (PTC) as precursors, and Ube has also developed fibers for which the Ti has been replaced by Zr or Al. All these fibers are distinguished by microstructural details that can induce major variations in their mechanical properties at high temperatures. The cross-linking process was originally by oxidation which led to the formation of the Si-C-O intergranular phase. The oxygen-rich intergranular phase induces strength losses around 1100°C and also facilitates Newtonian creep by grain sliding. The oxygen was largely eliminated by Nippon Carbon which began to cross-link by electron irradiation to produce Hi-Nicalon fibers. The introduction into the precursors, by the other two producers, of metallic alkoxides also introduces oxygen, and little advantage is found if the irradiation process is used; however, these precursors allow high pyrolysis temperatures and so elimination of oxygen and carbon. Near stoichiometric fibers from polymeric precursors are becoming available from the three manufacturers. The Hi-Nicalon-S fiber is produced from the Hi-Nicalon fiber, whereas the Tyranno-SA and Sylramic fiber from Dow Corning are made from oxygen crosslinked precursors to which sintering aids are added. Final pyrolysis is at around 1800°C in a controlled atmosphere. They contain no detectable intergranular phase, and the SiC grains develop to larger sizes than in the earlier fibers, up to 200nm. This has led to an increase in Young's moduli to around 400GPa. Free carbon does not seem to have been completely eliminated in the near stoichiometric fibers and is said to hinder grain growth. The larger grains and absence of an intergranular phase give much lower creep rates, strength retention, and resistance to high-temperature degradation. The Hi-Nicalon S fiber retains its strength up to 1400°C. Variations in the compositions of the near-stoichiometric fibers lead to considerable differences in creep rates, so further optimization and improvements in these fibers can be expected in the near future.

Oxide Fibers

Even stoichiometric SiC fibers will be limited by oxidation. Oxide fibers are available based on Al_2O_3, often combined with silica to limit grain growth and inhibit development of porosity as well as retard phase changes. Short fibers such as Saffil were developed by ICI in the early 1970s and are based on δ-Al_2O_3 with 3%vol SiO_2. Later, 3M produced the amorphous Nextel 312 fiber based on a mullite composition. These fibers can be used to reinforce Al. High-performance composites require continuous fibers with the capability to retain their properties to very high temperatures. Alpha-Al_2O_3 fibers have been developed by several companies since the late 1970s and retain their strengths up to 1000°C. They can be made by blending α-Al_2O_3 in powder form with a soluble Al-rich precursor to form a mixture that can be spun and fired in air to about 1300°C. The FP α-Al_2O_3 fibers, made by DuPont, were almost fully dense and had diameters of 20µm, grain sizes of about 0.5µm, and Young's moduli of 400GPa but were too brittle to weave. Later, α-Al_2O_3 fibers were made by Mitsui Mining under the name Almax, with diameters of 10µm; these fibers can be woven. They have a lower Young's modulus, around 340GP, due to considerable porosity. The latter two fibers lose strength from 1000°C due to grain boundary. Creep is observed from 900°C, and even superplastic behavior has been observed at ~1300°C. At such temperatures, no grain growth was seen in FP fibers unless an imposed strain was applied when growth of up to 40% occurred. Significant grain growth without induced strain is seen in Almax fibers due to internal residual stresses. Damage is due to the pileup of dislocations at triple points leading to cavitation initiating transverse intergranular microcracks. Creep rates are higher, and creep is more easily initiated in the Almax fiber. The Nextel 610 fiber has a diameter of 10µm and grains around 0.1µm; it can also be woven. This fiber contains a nucleating agent and grain growth inhibitor. Faster creep rates have been observed in this fiber than in the FP fiber due to the smaller grain sizes and chemistry at the grain boundaries.

Fibers with two phases have been made to hinder crack propagation and creep. DuPont produced a fiber containing 80% wt of α-Al_2O_3 and 20% ZrO_2 which showed slightly enhanced failure strains at room temperature and a delayed onset of creep, around 1100°C. Creep rates increased, however, with increasing temperature, and at 1300°C the advantage was lost. The Nextel 440 fibers are produced by a sol-gel process to give structures composed of 3 moles of alumina for 2 moles of SiO_2 with boria to restrict crystal growth. These fibers creep above 900°C, due to the presence of SiO_2, as do Altex fibers produced by Sumitomo Chemicals made of γ-Al_2O_3 and 15% wt SiO_2. The lowest creep rates for polycrystalline oxide fibers have been measured with the Nextel 720 fibers, which have the same Al_2O_3 to SiO_2 ratio as the Altex fiber but are fully crystalline. The different processing route produces dense fibers with a composition of 55% wt mullite in the form of aggregates, with dimensions of 0.5µm in which are embedded smaller grains of α-Al_2O_3. The large aggregates with irregular forms limit grain boundary sliding by reducing grain boundary diffusion paths, and creep rates for an applied stress of 1GPa are similar to those of Hi-Nicalon fibers, around 10^{-9}/sec at 1100°C. However, the fibers have proven to be extremely sensitive, at temperatures above 1100°C, to external contamination, which can initiate crack propagation and fiber failure.

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Sizings for Glass Fibers and Their Role in Fiber Wetting and Adhesion in Liquid Molding

Lawrence T. Drzal
Deptartment of Chemical Engineering
Composite Materials and Structures Center
Michigan State University
East Lansing, MI 48824-1226
Voice: (517) 353-5466
Fax: (517) 336-1634
E-mail: drzal@egr.msu.edu

Liquid molding of advanced composite structures having high strength and modulus depends on favorable thermodynamics of wetting and dissolution between the finish applied to the glass-fiber surface and the reacting liquid matrix. After fiber-drawing, commercial fibers used in liquid composite molding processes are coated with proprietary finishes that act as processing aids and contain coupling agents for long-term durability. Minimization of interfacial free energy provides the driving force for the formation of solid-liquid interfaces. In the ideal case, all adsorbed material will be displaced from fiber surfaces within each bundle and from between fiber bundles by the infiltrating resin. If this interaction is optimal, the infiltration should be completed without generating voids if rheological factors do not override interfacial forces. However, in fast-reacting systems like RIM polyurethanes, the time available for dissolution is less than 60 seconds. Research is underway to investigate fiber finish/matrix interaction in liquid composite molding. The objective is to understand and quantify the interactions between finished fiber surfaces with vinyl ester and urethane matrices and to identify the factors responsible for fiber/matrix bond formation in the time-dependent liquid composite molding environment—to enable the development of optimal finish composition and processing cycles.

A series of glass fibers was produced using finishes of known composition. The finishes consisted of film-forming resins and silane coupling agents. The film-formers were selected on the basis of their compatibility with and wettability by the matrix. The fibers were produced using commercial equipment and techniques to give a realistic finish content and distribution on the fiber surfaces. Wetting and solubility parameter studies were conducted on the finishes to provide the fundamental structure-processing-property relationships between the matrix and finishes. The film-former solubility parameters followed the same trend as the work of adhesion in terms of the interactions with the components of the polyurethane matrix. Single-filament Wilhelmy, scanning electron microscopy, and X-ray photoelectron spectroscopy were used to characterize the distribution of the finish on the fiber surfaces and the interior of the fiber tow. Unidirectional composites were produced via SRIM using a two-component polyurethane matrix. The microindentation method was used to determine the interfacial shear strength of the composites.

Fiber-matrix adhesion measurements indicated that adhesion was poor in cases where the finish was either incompletely wet by the matrix or unable to dissolve before the matrix gelled. Fiber-matrix adhesion was found to depend strongly on the compatibility of the finish with matrix components. The fibers that had a finish compatible with at least one component of the resin had substantially increased adhesion over fibers with a totally incompatible finish. The amount of finish applied to the glass fibers also influenced the interfacial shear strength. Composite shear strength measurements indicated that fiber/matrix adhesion translated into correspondingly high or low composite mechanical properties. The role of the finish constituents and the effect of processing conditions on fiber-matrix adhesion and composite interlaminar shear strength will be discussed.

Interfacial Design For Damage-Tolerant Composites

Nancy R. Sottos
Department of Theoretical and Applied Mechanics
University of Illinois at Urbana-Champaign
104 S. Wright Street, Urbana, IL 61801-2935
Voice: (217) 33-1041
Fax: (217) 244-5707
E-mail: n-sottos@uiuc.edu

Damage tolerance in composite materials is strongly influenced by fiber/matrix interface properties. Understanding how the interfacial toughness and frictional stress are correlated with the damage modes and size of the bridging zone is crucial for designing the composite for a desired application. The current study of the interfacial failure sequence during fiber push-out reveals the importance of fiber surface roughness and adhesion on damage evolution. Single fiber push-out tests were performed on model composites with carefully controlled interfacial surface roughness and adhesion. The entire push-out apparatus was placed in a circular polariscope to observe the interfacial failure sequence. The high concentration of photoelastic fringes at the crack tip was used to identify debond initiation and to measure the crack length as the debond progressed. The model composite material system consisted of a polyester fiber embedded in an epoxy matrix, which were chosen for their bifringent properties.

Push-out curves for polyester fibers with three different levels of average surface roughness (ρ_{avg}) are shown in Figure 1. Although the initial elastic portions of the push-out curves for samples of different roughnesses were nearly identical, the values of the maximum load and displacement at the onset of sliding were much higher for the rougher fibers. After the initial elastic (linear) part, the push-out curve for the rougher fibers (ρ_{avg} = 62.7nm and 86.4nm) becomes nonlinear, which corresponds to progressive debonding. Progressive debonding did not occur in the sample with the smoothest fiber (ρ_{avg} = 6.3nm). The rougher fibers introduce higher stresses at the interface, increasing the level of energy needed for crack propagation. Thus, the difference between the energy needed for propagation and that needed for initiation is smaller for rougher samples, and stable crack growth prevails. For smoother fibers, the debond initiation energy is high enough (compared to the debond propagation energy) to cause catastrophic (instantaneous) debonding. After complete debonding, the push-out load during frictional sliding increased dramatically with increasing roughness. However, the push-out force is expected to decrease as the fiber pushes out, due to the decrease in contact surface area. Such counterintuitive behavior is due to the strong influence of particle plowing and wear, the evidence of which can clearly be seen on the fiber surfaces after push-out.

The effects of interfacial adhesion were studied on samples with smooth fibers of nearly the same roughness (ρ_{avg} = 6-9 nm) with three different levels of adhesion. The addition of Dow Z-6070 dispersion agent (methyl-trimetoxysilane) significantly reduced the push-out peak load (Figure 2), while the addition of Dow Z-6032 coupling agent (aminoethyl-aminopropyl-trimethoxysilane) significantly increased the peak load, compared to a sample with no surface treatment. Again, the elastic parts of all three push-out curves were nearly identical. After the initial fluctuations in push-out force immediately after debonding, the force during frictional sliding was nearly the same for all three samples.

Interface properties such as the mode II interfacial toughness and coefficient of friction were extracted from the push-out data using well-known shear lag models. However, some of the experimental push-out curves could not be predicted accurately by shear-lag solution. In these cases, a more rigorous finite element analysis was used to determine the interfacial properties. Overall, these preliminary experiments indicate that the interfacial properties of the model composites can be systematically altered to create a range of damage modes.

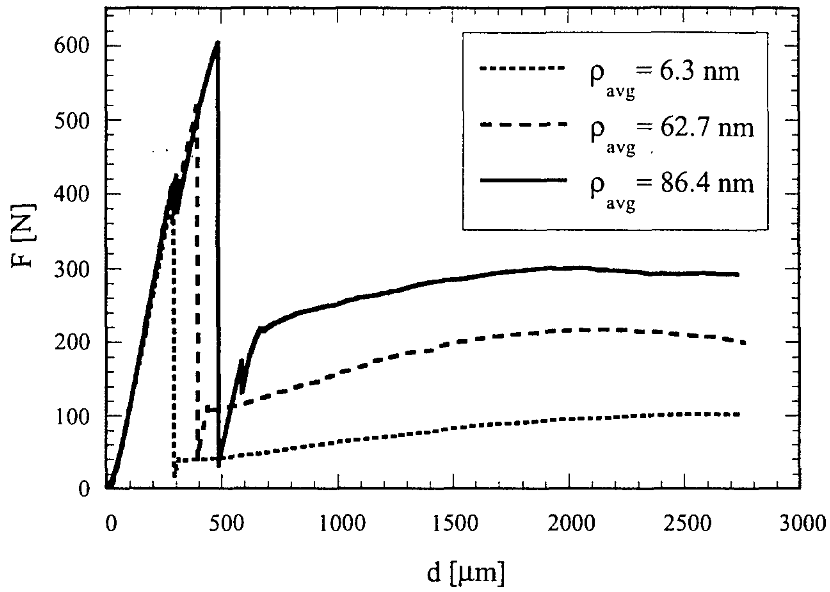

Figure1: Force vs. punch displacement data for two samples with different roughness.

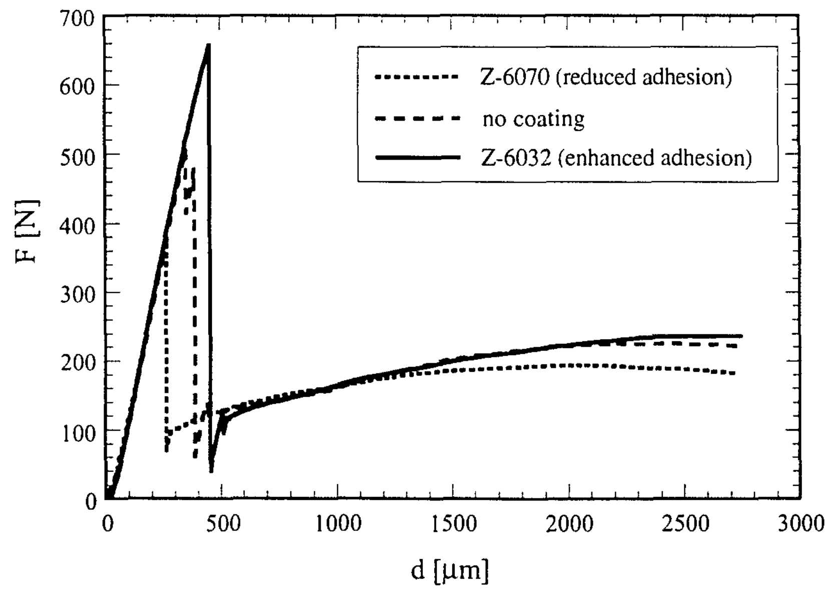

Figure 2: Force vs. punch displacement data for samples with different levels of interfacial adhesion.

Composites Research for Marine Structures

Yapa Rajapakse
ONR, U.S. Navy
Ship Structures Division (ONR 334)
800 N. Quincy St. (BCT1, Rm 528)
Arlington, VA 22217-5660
Voice: (703) 696-4405
Fax: (703) 696-0308
E-mail: rajapay@onr.navy.mil

Composite materials provide many attractive options in the design and utilization of affordable and reliable marine structures. They are being used increasingly in Naval structures. The loading on these structures and the environment in which they operate are quite different from those associated with familiar aerospace structures. The loads are three-dimensional and time-dependent; they are due to ocean waves, slamming, whipping, etc. The environment is severe; the presence of moisture, sea water, temperature variations, and hydrostatic pressure poses new challenges.

There are several important requirements in the design of composite marine structures. Affordability is an overriding concern in the large-scale use of composites. Thus, a major focus is on polymer-matrix composites, with increased emphasis on affordable composite systems, including resin transfer molded composites and sandwich structures. Other requirements include survivability, reliability, structural integrity, and durability.

The mechanics of "thick" composites (used in marine structures) is not as well established as the mechanics of "thin" composites (used in aerospace structures, etc.). To provide the scientific basis for the efficient design and use of composite materials in Naval structures, the Ship Structures and Systems Division of the Office of Naval Research (ONR), has established a research program on "Composites for Marine Structures." This program addresses a wide variety of fundamental issues associated with the design and use of composite ship structures in marine environments.

The objective of ONR's research program in composites is to establish physically based quantitative models for the thermomechanical behavior of polymer-matrix composites and composite sandwich structures subjected to multi-axial static, dynamic, and cyclic loading in severe environments, including extremes of temperature, moisture, sea water, hydrostatic pressure, and radiation fields. A balanced approach, integrating advanced experimental techniques, theoretical analyses, and computational methods, is used in the elucidation of the physical processes involved and in the establishment of quantitative models capable of predicting the behavior of composite structures in the marine environment. These structures include multifunctional, multi-layered composite systems, integrating structural composites and signature-reduction material systems.

An overview of current research and scientific accomplishments in the program will be provided in the presentation. Topics discussed will include moisture/sea-water effects, failure modes and failure criteria, three-dimensional constitutive equations, hydrostatic pressure effects, compression failure, dynamic constitutive equations, strain rate effects, structural failure modes, coupling between material and structural failure, multifunctional sandwich structures, and response of composite structures to dynamic/shock loading. Dynamic failure is receiving special attention in the research program; investigations that utilize full-field optical techniques for deformation fields, coupled with high-speed photography capable of 100 million frames per second, will be discussed.

Examples of current and planned applications of composites in marine structures in the U.S. and in Europe will be presented, including composite mine-hunter hulls, submarine sonar domes, advanced enclosed mast structures, topside structures, and helicopter hangars.

Mechanics of Wavy Composites

Charles W. Bert
Perkinson Chair/G. L. Cross Research Professor
School of Aerospace and Mechanical Engineering
The University of Oklahoma
Norman, OK 73019-1052
Voice: (405) 325-1736
Fax: (405) 325-1088
E-mail: bert@mailhost.ecn.ou.edu

Continuous-fiber composites can have defects not found in ordinary materials. These defects include fiber-matrix debonding, delamination, fiber breakage, and fiber or layer waviness. Property degradation due to the first three types of defects has been investigated extensively, while that due to the fourth type, which is the subject of this paper, has not received as much attention. Fiber or layer waviness can be caused by a number of factors including matrix shrinkage during curing, the filament winding process, and fiber weaving or braiding. The probability of the presence of waviness is greater for thicker section composites than for thin ones. Thus, with the trend toward thicker section composites, the importance of wavy composites is increasing.

This paper provides a critical review of the literature on the mechanics of wavy composites, including both mathematical modeling and experimentation. The literature includes early Russian research as well as more recent research in the U.S. The types of composites range from biological (a rat's tail) to polymer-matrix composites with metallic and other materials as fibers.

Fiber waviness causes decreasing stiffness as the composite is loaded further and further in compression due to the tendency toward fiber buckling. In contrast, as the wavy composite is loaded further and further in tension, the stiffness increases, due to the tie-bar action. This different elastic behavior in compression and tension has interesting and important consequences for beam loading. Although most specimen configurations have been prismatic bars or plates, there have been some analytical as well as experimental investigations on tubular specimens subjected to uniform external pressure.

Also, the bending-stretching-twisting action of helically curved fibers, acting either individually or in bundles or cords such as in tire cord/rubber, is discussed. Dynamic as well as static investigations are mentioned.

The presentation concludes with suggestions for further analytical, numerical, and experimental research.

On the Use of Ply-Failure Criteria In Multi-Ply Laminate Design

Albert S. D. Wang
Drexel University
Department of Mechanical Engineering
32nd and Chestnut Street
Philadelphia, PA 19104
Voice: (215) 895-2297
Fax: (215) 895-1478
E-mail: awang@coe.drexel.edu

In design and analysis of multi-ply laminates, failure criteria that are based on the computed ply stresses are often used in preliminary design as well as in late-stage lamination optimization. This approach has enjoyed immense popularity for decades, both in industrial practice and in training of engineering students; the latter is evidenced in many a course and/or textbook related to mechanics of composites.

The central theme of this presentation is to explain why the popular ply failure criteria could be woefully inadequate even for preliminary laminate design.

To this end, we first trace back to developments of the stress-based failure criteria, from von Mises to R. Hill and to some prominent modern-time laminate failure analysts; here, we show how the physical failure theory of von Mises, which is based on deformation mechanisms in the material microstructure had become merely a class of mathematical failure theories to be correlated only with macroscopically measured "ply strengths."

Secondly, we document experimental evidence and show that most of the purported "ply strengths" used in conjunction with the ply failure criterion may not be determined uniquely as a "ply material property," especially when the ply is adhered to or constrained by other material plies such as in multidirectional laminates.

The above-mentioned limitations of the ply-stress-based failure criteria have been known in composite research circles for a long time, but a successful remedy of the situation has been lacking.

It is felt that we need to come back earnestly to developing one or more physical failure theories that are based on deformation mechanisms in, at least, the ply-structure of the laminate. A possible approach along this theme is suggested at the conclusion.

Predictive Methodologies for Damage Tolerance: Foundations for Virtual Design

Kenneth L. Reifsnider
Materials Response Group, Department of Engineering Science and Mechanics
120 Patton Hall
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
Voice: (540) 231-5316
Fax: (540) 231-9187
E-mail: mrl@vt.edu

The design process is becoming more automated, more computationally intensive, and more collaborative, especially when advanced materials are used. However, the demands on the design methodology are also increasing. In order to cut costs, the concept of design in virtual environments is now being developed. The basic premise is that most design decisions and adjustments can be made in a virtual representation of the component and its performance, so that the cost of testing, characterization, substructuring, and prototypes can be greatly reduced. Preliminary experience with such efforts has resulted in savings of as much as 35 percent on total cost to a final product using such methods. However, representations of performance used for such virtual designs must be based on models which are remarkably robust, i.e., that can estimate properties and performance over the full range of expected or possible operating conditions. The present paper will address the consequences of such requirements for models that can be used to estimate the remaining strength and life of composite systems, with special attention to the problem of constructing constitutive models that are explicit functions of extensive variables such as temperature.

The concepts to be discussed are illustrated in Figure 1. To design a component for a specified strength and life, one must begin with the determination of quasi-static properties as inputs to the finite element analysis typically used for design computations. However, if one is to design for durability and damage tolerance, it is also necessary to have a model that will predict how those properties change during service and the consequences of those changes on remaining strength and life. Such a model (the critical element model in the present case) must also be based on representations of properties and the dependence of those properties on time, temperature, and other external variables. However, one rarely sees a constitutive equation such as Hookes Law written as an explicit function of temperature, for example. Models based on equations that do not depend on external variables such as temperature cannot be used in robust virtual design environments, since it cannot be assumed that the operating temperature (or other external variables) of such designs is constant.

The present lecture will present a new methodology for estimation of the temperature dependence of the stiffness of polymers and polymer-based composite systems, across all transitions such as the T_g of the materials. Then the critical element method will be used to construct a methodology for the estimation of remaining strength and life in the presence of changing temperature. Finally, the models will be integrated with a commercial analysis code to achieve a robust tool for design in real or virtual design environments. Examples of selected predictions will be compared to experimental data. The limitations of the method will be identified, and needs for continuing research will be defined.

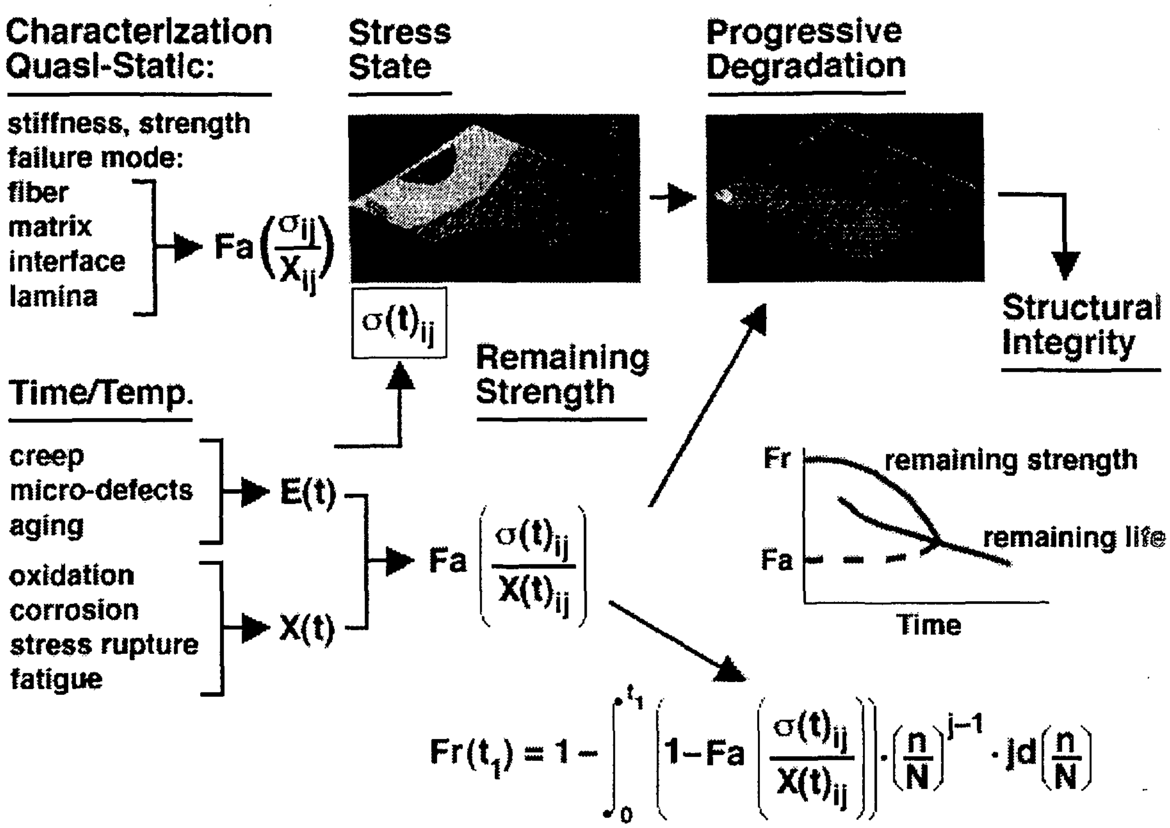

Figure 1: Concepts to be discussed.

Experiments were conducted on a 3-in. x 11-in. x 1/8 in. end-gated plaque containing several ribs. The orientation in a cross-flow rib and a flow-direction rib were measured by image analysis on a polished cross-section. The predictions for fiber orientation compare quite well with the experiments, suggesting that the model is accurate. Both calculations and experiments display effects that are not represented in Hele-Shaw models of injection molding. Clearly, detailed 2-D and 3-D calculations of the type presented here can be used to represent the flow, heat transfer, and fiber orientation near 3-D molded features.

The main simplifications of the model—that viscoelasticity and the coupling of fiber orientation to rheology are neglected—do not appear to affect the results for fiber orientation. Our general approach of analyzing the mold globally using a Hele-Shaw model and then analyzing features locally using 2-D or 3-D models appears to work well. However, it is essential to model the transient filling of the feature, since there may be little or no flow in portions of the feature after it has been filled. It is also important to model the flow past the feature after it has been filled, since there may be significant changes in the temperature and orientation during this period.

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Characterization of Shear Behavior in Sheet Forming of Both Thermoplastic and Thermoset Composite Laminates

Patrick J. Mallon
University of Limerick
Plassey Technological Park
Room C0063 University Main Block
Limerick, Ireland
Voice: (353) 61-202-700
Fax: (353) 61-202-944
E-mail: patrick.mallon@ul.ie

The deformation mechanisms involved in the sheet forming of continuous-fiber-reinforced composite laminates includes interply shear together with longitudinal and transverse shear of the individual plies. An understanding of these mechanisms is essential for the process modeling of both sheet forming of thermoplastic composites and hot-drape forming of thermoset composites. In this research, the interply shear behavior of both thermoplastic and thermoset composite laminates has been experimentally characterized, while the longitudinal and transverse shear characteristics of unidirectional plies have been investigated experimentally using both a model composite together with carbon-fiber-reinforced PEEK (APC-2).

Previous research [1] has characterized the interply shear behavior for both a unidirectional thermoplastic composite (APC-2) and a woven carbon-fiber-reinforced PEI (Cetex). The shear stress/shear velocity behavior was established as a function of temperature, normal pressure, and fiber orientation. Using the same parallel plate apparatus, the interply shear characteristics of both unidirectional and woven (Twill and 5HS) carbon-fiber-reinforced epoxy have been established over the temperature range from 60 to 100°C and at normal pressure, 30kPa. While the interply shear results for the thermoset composite exhibited a pattern of behavior similar to that of the thermoplastic composites for both temperature and normal pressure variations, the resin systems appear to influence the shear-rate dependence and the levels of shear stress. Further interply shear experiments were conducted on non-crimp-fabric (NCF) thermoset composites over a temperature range from 80 to 120°C and normal pressure of 30kPa. The shear stress for these materials displayed a low shear-rate dependence over the test conditions.

The longitudinal and transverse shear viscosities, μ_L and μ_T respectively, were established for a model composite consisting of long nylon fibers, 0.2mm diameter, in a Newtonian fluid using a parallel plate apparatus, designed to produce a constant shearing action. For a fiber volume fraction (V_f) of 60%, μ_T was larger than μ_L for shear rates of 0.006 to 0.3s^{-1}. The transverse viscosity increased significantly for values of V_f greater than 50%, indicating a transition from free transverse flow to a very restricted type of flow within the constant gap width of 4.0mm. The longitudinal shear behavior of APC-2 was evaluated using a parallel plate apparatus, and the results demonstrated what appeared to be a significant fiber entanglement effect.

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Application of Nondestructive Techniques to Processing and Characterization of Composites

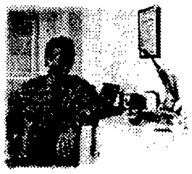
Robert E. Green, Jr.
Center for Nondestructive Evaluation
The Johns Hopkins University
3400 N. Charles Street
Baltimore, MD 21218
Voice: (410) 516-6115
Fax: (410) 516-7249
E-mail: cnde@jhu.edu

Process Control: Composite materials are normally manufactured by hand layup and autoclave cure and filament or tow placement with a winding machine and cured in place. The two parameters routinely monitored are the temperature and the pressure applied to the filaments, tows, or laminates. Sometimes a dielectric sensor is mounted between two composite plies in autoclave curing to measure the ionic conductivity. No technique exists to optimally monitor the mechanical properties during the curing process, although the mechanical properties are the most important ones for all composite structures. Ultrasonic systems are optimum for this purpose. The wave speed is a function of the elastic modulus and density of the composite, while the attenuation is a monitor of the change in viscosity of the resin. Because of the requirement to control the manufacturing process under conditions of high temperature, contact ultrasonics cannot be optimally used. Recently a prototype in-process non-contact ultrasonic system for monitoring composite tape placement with on-the-fly curing has been practically applied in industry. This system is based on laser generation and air-coupled capacitive transducer detection. A spatial array of illumination lines permits narrowband generation of surface ultrasonic waves. The decrease in bandwidth of the generated waves combined with the use of a detection transducer with a matching bandwidth produces a significant increase in the signal-to-noise ratio. The laser light was delivered to the carbon/PEEK composite tape by a special fiber-optic bundle which enhanced the flexibility of the system. Depending on the width of the optical fiber and spatial arrays, the entire width of a tape being placed can be monitored without mechanical scanning. Subsurface regions of poor consolidation and delaminations were successfully detected.

Materials Characterization: A number of nondestructive techniques have been used to evaluate composite materials, among which are ultrasonic A, B, and C-scan, ultrasonic velocity and attenuation, ultrasonic second harmonic generation, acoustic microscopy, acoustic emission, thermography, real-time high-speed digital/video laser speckle decorrelation, magnetic resonance imaging, radio-opaque penetrant enhanced x-radiography, and eddy current. Mechanical resonance spectroscopy has been used to measure second order (linear) elastic moduli. X-ray tomography has proven to be an extremely useful nondestructive evaluation technique, but the equipment is expensive and poses a radiation hazard. On the other hand, x-rays travel in straight lines or fan beams as desired and are not refracted by any anisotropy in the material. The equipment for ultrasonic tomography is relatively simple, inexpensive, and extremely safe, and the anisotropy of composite materials can be determined a priori because the particular lay-up or fiber placement of composite materials is controlled during the manufacturing process and mimics that of single crystals for which the general ultrasonic propagation characteristics are well known. Research has been conducted to make full use of all information with regard to ultrasonic wave propagation in anisotropic materials to develop an ultrasonic tomography technique for defect imaging in anisotropic materials, particularly composites. For any given direction of the normal to the wavefront ("propagation direction"), the direction of the energy flux vector (energy propagation path) can be computed. By combining this information with knowledge of the geometry of the test object in the appropriate manner. tomographic images may be obtained.

Fatigue Damage Monitoring: Most fatigue tests on composite materials have been performed in tension-tension or tension-compression on relatively long, thin laminates. The use of such specimens often does not yield correct compression response data, because of long column buckling problems. In some cases, the test specimens were restrained from buckling by side supports, which makes the resulting data even more questionable. Compression-compression fatigue tests have been run on relatively thick graphite-epoxy composite specimens, possessing square cross-sections with notches cut in the through-thickness direction at mid-height of each side to localize stress-induced damage. Changes in the mechanical characteristics were observed after the first cycle of a fatigue test using real-time high-speed digital/video laser speckle decorrelation. Combined ultrasonic attenuation and acoustic emission systems monitored the development of fatigue damage during relatively long-term fatigue testing. Ultrasonic C-scan imaging was used to locate delaminations, interlaminar cracks, and intralaminar cracks. Infrared thermography monitored heat generated in the specimen during the course of fatigue.

Advances in Polymer Matrix Design and Performance



James C. Seferis
Polymeric Composites Laboratory
Box 351750, Benson Hall
University of Washington
Seattle, WA 98195-1750
Voice: (206) 543-9371
Fax: (206) 543-8386
E-mail: seferis@cheme.washington.edu

Over the past few decades, there has been an increasing number of thermosetting matrices utilized in composite systems and film adhesives. The components in these matrices are proprietary, which causes problems in manufacturing and proper utilization by end-use consumers. Due to thc proprietary nature of the material, both prepreg and adhesive modeling methodologies have been developed so that these materials can be understood from a fundamental process–structure–property viewpoint. The methodologies provide a clear path to efficiently reverse-engineer, model-engineer, and finally re-engineer the original commercial system. The goal of reverse engineering is to understand the process–structure–property relationships of the material, not to discover the precise chemical composition. From this understanding, model systems can be developed to understand the effects of each of the constituents on the final material This information can be utilized for re-engineering commercial materials with no significant changes to the chemistry.

Most of the commercial matrix materials have been designed with an excessive number of components that have added to the complexity of understanding these systems. Although these materials may perform well in some applications, they may not meet the requirements of others. Past work has shown that simple matrices, those with limited components, can be made to perform as well as or better than the complex commercial matrices if properly designed. This can be accomplished only if the effects of each component in the formulation are understood as to how they effect the system as a whole. As a result, with changing only the formulation procedure and adducting sequences, the properties and structure of the final cured matrix can be changed drastically. Therefore, the same material that did not perform well for a specific application may be able to be re-engineered through only the formulation procedure for better properties.

Past work has also focused on probabilistic models of networked thermosetting polymers. The model system used in these studies was based on TGDDM–DDS systems, consisting of tetrafunctional/octofunctional epoxide mixtures and curing agents. The probabilistic models produced values of the average molecular weight of the chains between crosslinks (M_c). Dynamic mechanical analysis successfully confirmed these findings when the M_C of the system was found experimentally through both the modulus and T_g shift methods. Although these probabilistic methods have shown promise, they have been limited to two and three constituent systems. Attempts have not been made to extend these models to toughened systems. This is primarily due to the limitations of probabilistic modeling for these systems. Accordingly our recent studies have focused on the junction of these arithmetic modeling and adducting areas of research. To aid this new endeavor, it was necessary to employ aspects of fuzzy logic and "possibilistic" modeling. This new method of modeling is providing for the advent of a second phase due to the addition of a toughening agent, and its effects on the final material properties. Mathematical models are also being created that are capable of predicting the effects of adducting and processing changes on final material structure and properties.

Collectively, we believe that advances in polymer matrixes for high-performance composites are still possible by proper designs and standardizations of technology through a systemic methodology.

Performance/Durability Issues of Advanced Composites in Civil Infrastructure

Robert L. Sierakowski
AFRL / MN
101 West Eglin Blvd
Suite Ste 105
Eglin AFB, FL 32542-6810
Voice: (850) 882-6167
Fax: (850) 882-3006
E-mail: sierak@eglin.af.mil

The performance/durability issues associated with the introduction of advanced composite materials for use in civil infrastructure is previewed as related to materials for infrastructure applications and civil engineering design practice.

The opportunity for the introduction of advanced composite materials is presented with background information on the current state of the nation's infrastructure. This consists of all industrial and public works that support our daily activities including bridges, airports, parking garages, waste treatment plants, and other constructed facilities. As a specific example of the report card on the state of the nation's infrastructure, the state of U.S. bridges is exemplified. Estimates indicate that of the approximately 600,000 U.S. bridges inventoried, one-third are rated as structurally deficient or functionally obsolete. Approximately 1000 per year fail, must be replaced, or traffic detoured to accommodate bridge deficiencies. There is currently, an $8-billion backlog to meet existing maintenance and replacement needs, while current expenditures are $5 billion per year. Looking ahead to developments in the 21st century, priority spending needs at the government level will continue to decline for budgets needed for new and repair of existing infrastructure. In its current state, the bulk of U.S. infrastructure has been constructed using steel-reinforced cement and steel structural shapes. The use of steel in constructed facilities can lead to failures and/or costly repairs attributed to accelerated corrosion with the material. As an example, it is estimated that the cost of replacing distressed steel decks will cost in excess of $20 billion due to corrosive deterioration. Thus, there is a need for new materials that are corrosion-resistant and high-strength and that can be produced at high volume and low cost as replacement for traditional materials. To reinforce the potential market share associated with materials investment in public works, it is estimated that in excess of $75 billion is spent annually on materials. As such, the construction industry thus represents the single largest U.S. market for any new material.

The introduction of advanced materials into civil infrastructure also requires an understanding of the civil engineering procurement process, where it is succinctly stated that designers design and constructors construct. The construction industry itself represents 9% of the GNP and is a $500 billion industry. It consists of over 1 million companies with gross profit margins of 2.5–5% and is built upon a lowest bid mentality. It is also based upon cultural factors associated with past experience defining acceptable technology, institutionalized relationships which define the relationship between the designer and constructor, and is plagued by tort liability challenges. The designers of civil infrastructure are licensed engineers who design in accordance with prescribed codes such as AASHTO, BOCA, and ACI. Design is promoted by trade associations such as ACI, AISI, AISC, ATI, and SPI.

Turning now to design approaches using advanced composite materials, it is important to distinguish between government and civilian design processes. Composite design in government is rooted in a design, build, test, redesign, and retest approach integrated with certification, quality control, acceptance, and further integrated with computer modeling and simulation, use of manufacturers' test data, and conduct of special tests. In the civil infrastructure area, the drivers are specialty product needs or specific structural elements produced by general-purpose processing techniques.

Factoring all the previous remarks, the desirable material/structural attributes to meet civil infrastructure needs are as follows:

- simple and easy application,
- easily handled with less manpower,
- capable of being fit to any shape,
- no welding and no solvent,
- high strength and light weight,
- excellent durability, and
- cost effective.

For designers to introduce these materials into existing practice, the following is needed:

- a change in designer mindset on the use of brittle materials,
- standardization and experience of design and construction as keys to spreading the technology,
- availability of the methodology known to owners and designers, and
- reliable and actual long-term durability data.

It is apparent that performance comparable to existing materials and durability are key attributes to the use of advanced composite materials in civil infrastructure. Durability within the framework of the civil engineering community is defined as the capacity of a product, component, system, building, or structure to perform over a specified period of time the function for which it was intended. This definition does not negate a designer's responsibility to consider the level of maintenance, repair, or replacement that may be required over the design life of the structure. Without citing specific durability issues and concerns related to materials attributes and designer needs, an example for bridge structures is presented. A key element for consideration of bridge designers in the 21st century will be life-cycle cost. This includes provision for systematic maintenance and management giving highest priority to high-quality inspection, repair and reinforcement, the extension of service life of existing bridge structures with minimal reconstruction and replacement, minimum future maintenance for new bridges, and well-designed permanent bridges. Indeed it has been said that the 21st century is the "age of maintenance" and the "age of advanced composites" (M. Uemura, Tokyo).

Probabilistic Evaluation of Composite Performance and Durability

Christos C. Chamis
NASA Glenn Research Center
Structures Division (MS 49-8)
21000 Brookpark Road
Cleveland, OH 44135
Voice: (216) 433-3252
Fax: (216) 977-7051
E-mail: cchamis@lerc.nasa.gov

Aerospace structures are complex assemblages of structural components that operate under severe and often uncertain service environments. They require durability, high reliability, light weight, and high performance at an affordable cost. Composite materials are potential candidates for meeting these requirements. Composite materials possess outstanding mechanical properties with excellent fatigue strength and corrosion resistance. Their mechanical properties are derived from a wide variety of variables such as constituent material properties and laminate characteristics (fiber and void volume ratios, ply orientation, and ply thickness). These parameters are known to be uncertain in nature.

To account for various uncertainties and to satisfy design requirements, knockdown (safety) factors are used extensively. These knockdown factors significantly reduce the design load of composite structures which result in substantial weight increase but without a quantifiable measure of their reliability. This paper describes an alternate method which determines the structural reliability. This method is embedded in the computer code IPACS (Integrated Probabilistic Assessment of Composite Structures) [1] for a comprehensive probabilistic assessment of composite structures. Figure 1 is a schematic of IPACS. Since the cost is a major driver for a structural design, optimization techniques should be sought to achieve the balance between maximum reliability and minimum cost. In this paper, reliability-based cost optimization is conducted to assess the risk and cost tradeoffs.

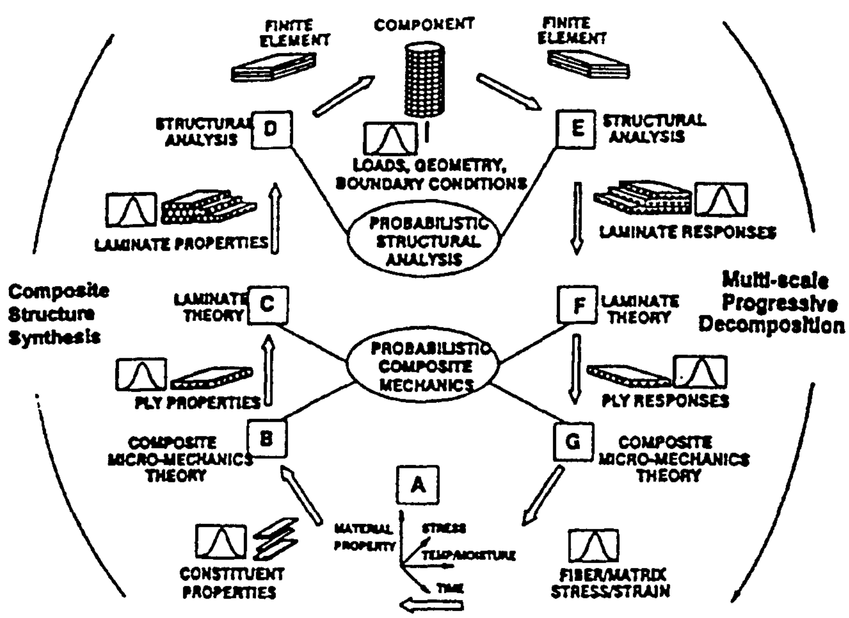


Figure 1: Concept of probabilistic assessment of composite structures.

Risk and cost tradeoffs have been simulated using a probabilistic method [2]. The probabilistic method accounts for all naturally-occurring uncertainties including those in constituent material properties, fabrication variables, structure geometry and loading conditions. The probability density function of first buckling load for a set of uncertain variables is computed. The probabilistic sensitivity factors of uncertain variables to the first buckling load is calculated. The reliability-based cost for a composite fuselage panel is defined and minimized with respect to requisite design parameters. The optimization is achieved by solving a system of nonlinear algebraic equations whose coefficients are functions of probabilistic sensitivity factors. With optimum design parameters such as the mean and coefficient of variation (representing range of scatter) of uncertain variables, the most efficient and economical manufacturing procedure can be selected. In this paper, optimum values of the requisite design parameters for a predetermined cost due to failure occurrence are computationally determined. For example, the results for the fuselage panel (Figure 2) show that the higher the cost due to failure occurrence, the smaller the optimum coefficient of variation of fiber modulus (design parameter) in the longitudinal direction.

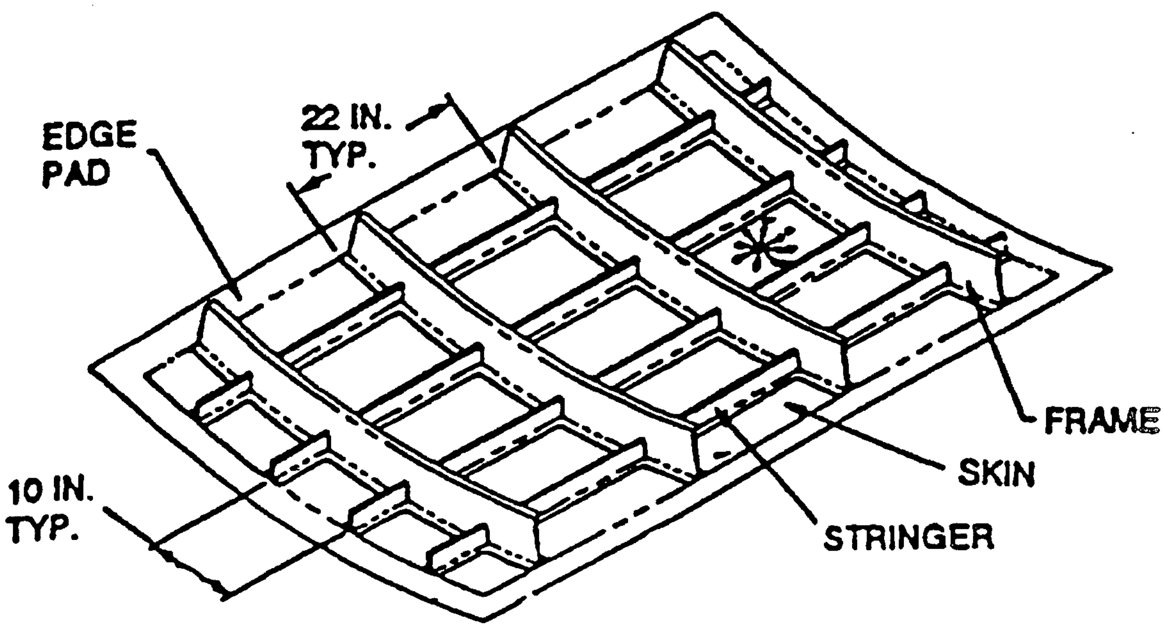


Figure 2: Lower side panel component.

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Polymer Composites for Tribology Applications

Klaus Friedrich
Institut für Verbundwerkstoffe GmbH (IVW)
University of Kaiserslautern
Erwin Schrodinger Str. 58
Kaiserslautern, 67663 Germany
Voice: (49) 631-201-7201
Fax: (49) 631-201-7198
E-mail: friedrich@ivw.uni-klde

Polymeric materials containing different fillers and/or reinforcements are frequently used for applications in which friction and wear are critical issues. Exact design of the materials depends on the requirement profile of the particular application. That means friction coefficient and wear resistance are not actually material properties but systems properties—i.e., they depend on the system in which the materials must function. Quite often, sliding is the dominant wear mode, and the materials have to be designed for low friction and low wear against smooth metallic counterparts (e.g., as gears or bearings); sometimes, however, a high coefficient of friction, coupled with low wear, is required (e.g., for brake pads or clutches).

This contribution summarizes various projects in this research field that are currently in progress at IVW:

(a). **Friction and wear studies of various short-fiber-reinforced injection-molded thermoplastic-matrix systems, used for sliding wear applications against steel counterparts [1]**. Particular focus is on high-temperature-resistant thermoplastics, filled with carbon fibers and internal lubricants, to enable operation under low friction and wear at elevated temperatures as sliding elements in, for example, textile drying machines [2, 3].

(b). **Systematic studies on the sliding wear resistance of continuous fiber/polymer composites, in order to develop hybrid composites showing synergistic effects in their wear properties.** In particular, the effects of various thermosetting and thermoplastic matrices, of different types of fibers (aramid, glass, carbon) and of different fiber orientations are compared with each other. The studies resulted in the recommendation of a hybrid composite, having both carbon fibers under parallel and aramid fibers under normal orientation, embedded in a high-temperature-resistant thermoplastic matrix. For further reduction of the coefficient of friction against the steel counterparts, additional PTFE fibers interwoven with the other two types of fibers were suggested [4].

(c). **Finite element modeling of the stress conditions in the contact region between the steel counterpart asperities and the continuous fiber/polymer composite surface as a function of fiber orientation, sliding direction, and contact pressure.** Further steps in this direction were aimed at (a) correlating the stress conditions in the components of the composite with its wear behavior, and (b) studying the local temperature development and the effects of a transfer film or wear debris layer between the mating partners [5].

(d). **Manufacturing of self-lubricated journal bearings by thermoplastic filament winding processes, using hybrid yarns.** The bearings are supposed to have low friction and high wear resistant properties at high-pressure/low-velocity sliding conditions against steel shafts. The cross-sections of the walls of these bearings have a variable structure, with an inner layer incorporating wear-reducing aramid and friction-reducing PTFE fibers and an outer layer consisting of a higher volume fraction of reinforcing glass fibers, so as to give the bearing high stiffness, strength, and creep resistance. Another possibility is to use the friction- and wear-optimized inner layer as an insert for injection molding of short-fiber-reinforced thermoplastics in order to verify more complex geometries, for example, as flange bearings [6].

(e). **New fundamental studies on the development of functionally gradient materials using various centrifugation techniques.** The objective was to demonstrate that a gradient in wear resistance and other properties as a result of a gradient in short fiber distribution can be created over the cross-section of the samples or components produced [7].

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Composites: The Good, the Bad, and the Ugly

Roy L. McCullough
Department of Chemical Engineering and
Center for Composite Materials
University of Delaware
Newark, DE 19716
Voice: (302) 831-2765
Fax: (302) 831-8525
E-mail: mcullough@ccm.udel.edu

The objective of this presentation is two-fold: First, as the closing speaker of the symposium, I intend to summarize the key points made by the previous speakers and issues developed in the forum. As a second objective, I wish to recount the progress made in polymeric composites from a personal (and perhaps biased) perspective.

The modern focus on composite materials was prompted by the needs of the space program and supersonic flight for lighter, stiffer, and stronger materials. Fortunately, prior knowledge was available to serve as a foundation. The composite concept had been known since biblical times; nature had provided examples such as wood and abalone shells to verify the efficiency of composite structures. In more recent times, glass-fiber-reinforced plastics had established the viability of composite materials; laminated plywood and fiber-reinforced tires provided elements for a design methodology.

We must admire the audacity of the early visionaries—they were able to persuade designers that airplanes could be made from "string and glue." Considerable enthusiasm was generated for composite materials, as reflected by slogans such as "the age of composites," the "future is composites," etc. (I do not have a precise count, but I believe that at one point the proliferation of slogans outpaced the production of composite materials.) This enthusiasm was needed, since let's face it, composite materials are innately ugly. They possess neither the warmth of wood nor the luster of metals. Their untreated surfaces are rough and crude, leading detractors to refer to them as "compost materials." Anything this ugly had better be good—and they were.

Over the intervening decades, composites science and technology made great strides. New societies were formed and a host of new journals initiated. (A bilious businessman claimed that the most profitable composites business was journal publications.) Along with the good successes, there were some bad technical and marketing failures accompanied by ugly consequences. Nonetheless, composite materials are still capturing the imagination of new generations of scientist and engineers who are exploring new and exciting uses of composite materials for defense as well as civil infrastructure. I eagerly await an output of new slogans.